LA-UR-21-20030
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Title: Heavy Flavor and jet studies for the future Electron-Ion Collider

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Intended for: The VI-th International Conference on the Initial Stages of High-Energy Nuclear Collisions, 2021-01-10/2021-01-15 (Rehovot, Israel)

Issued: 2021-01-14 (rev.1)

Heavy Flavor and jet studies for the future Electron-Ion Collider

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IS2021
The VIth International Conference on the
INITIAL STAGES
OF HIGH-ENERGY NUCLEAR
COLLISIONS

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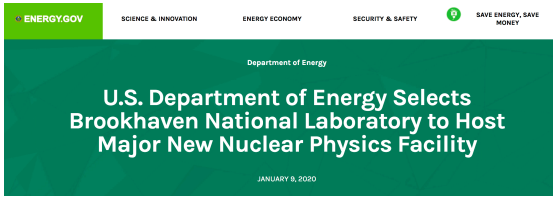
Outline

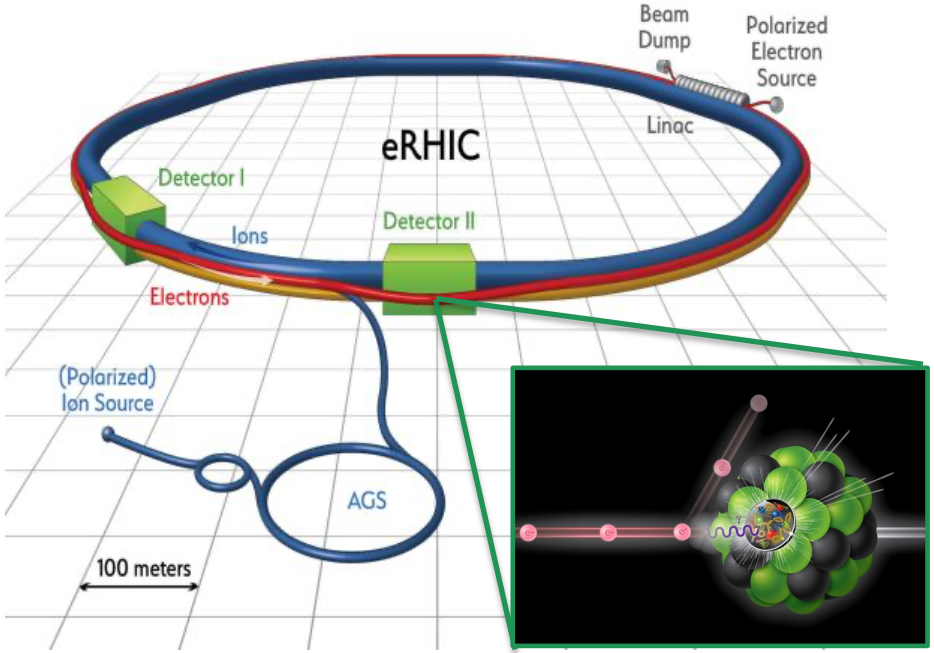
- What is the Electron-Ion Collider (EIC)?
- Why and how to measure heavy flavor at the EIC?
- Initial forward silicon tracker detector design and tracking performance.
- Open heavy flavor and jet studies in simulation.
- Summary and outlook.

The Electron-Ion Collider will bring new opportunities in high-energy nuclear physics

- The proposed Electron-Ion Collider (EIC) CD0 has been announced and the site is selected to be BNL.

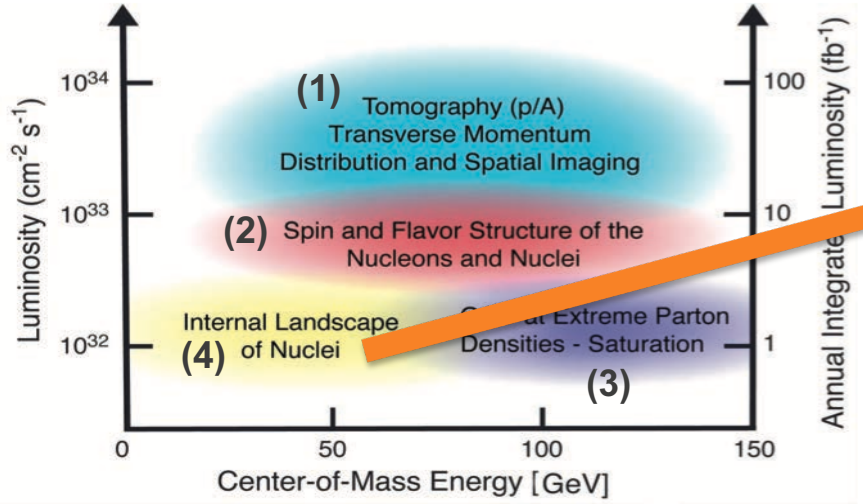


- e-p collisions at the EIC:
  - (Polarized) p, d/^{3}He beams at 41-275 GeV.
  - (Polarized) e beam at 5-18 GeV.
  - Instant luminosity L_{int} ~ $10^{33\text{-}34}$ $cm^{-2}sec^{-1}$. A factor of ~1000 higher than HERA.
  - Bunch crossing rate: 1-10 ns.
- e-A collisions at the EIC:
  - Multiple nuclear species (A=2-208) and variable center of mass energies.
  - Instant luminosity L_{int} ~ $10^{33\text{-}34}$ $cm^{-2}sec^{-1}$.
  - Bunch crossing rate: 1-10 ns.

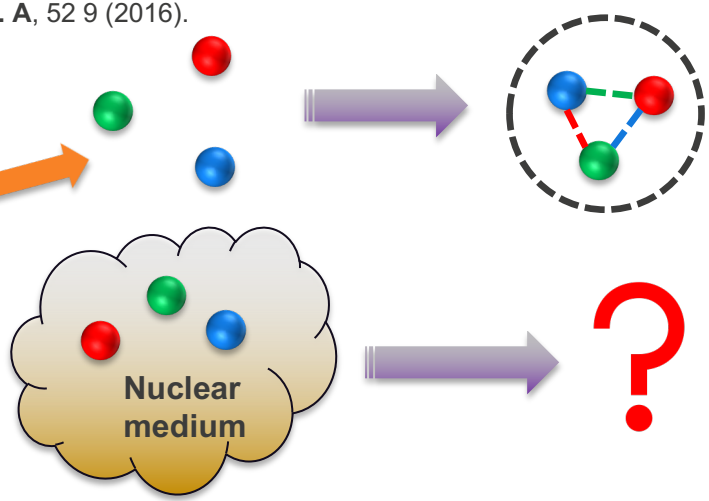


Fundamental questions to be explored by the EIC

- The proposed EIC will (1) precisely study the nucleon/nuclei 3D structure, (2) help address the proton spin puzzle and (3) explore the nucleon/nuclei parton density extreme – gluon saturation.
- It will provide a clean environment to (4) explore how quarks and gluons form visible matter inside the vacuum/medium, which is referred to as the hadronization process.



A. Accardi et al, **Eur. Phy. J. A**, 52 9 (2016).



Heavy quarks play a special role within the EIC science portfolio (I)

- Heavy quarks c (charm M_c=1.3 GeV), b (bottom M_b=4.5 GeV) are heavier than the proton. They are created in the initial collision and can probe the parton (quark or gluon) evolution processes inside the vacuum and the medium.

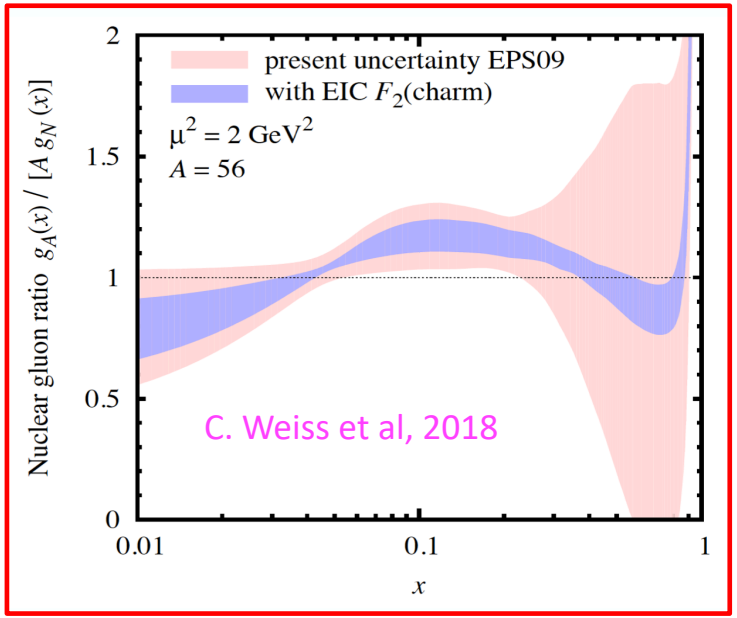
$$d\sigma_{jet} = f(x_B) \times H$$

Distribution of quarks and gluons in nucleons/nuclei

Accurately computable perturbative part

- The measured heavy flavor jet cross section contains information about the initial nucleon/nuclear parton (quark or gluon) distributions.

gluon nPDF ratio



Heavy quarks play a special role within the EIC science portfolio (II)

- The measured heavy flavor jet/hadron cross section contains the information about both the initial nucleon/nuclear parton distributions and the final state fragmentation processes.

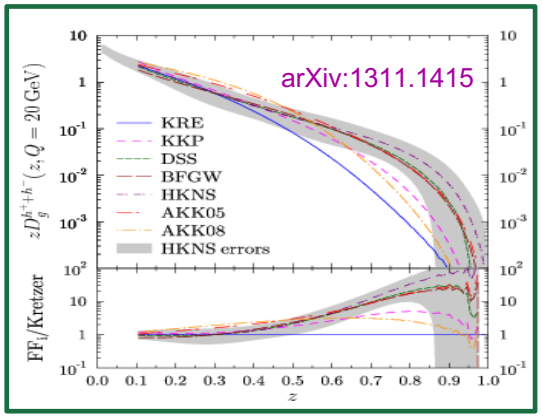
$$d\sigma_{\text{jet [hadron]}} = f(x_B) \times H \; [\times D(z_h)]$$

Distribution of quarks and gluons in nucleons/nuclei

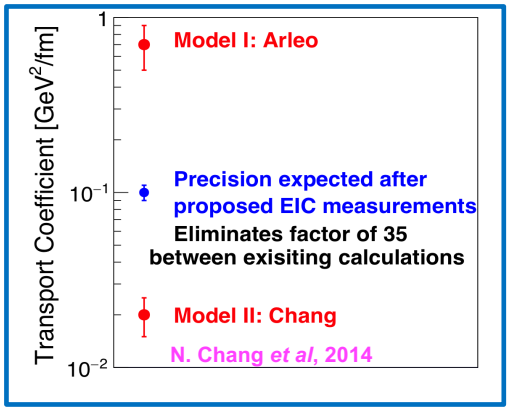
Accurately computable perturbative part

Fragmentation function

gluon FF



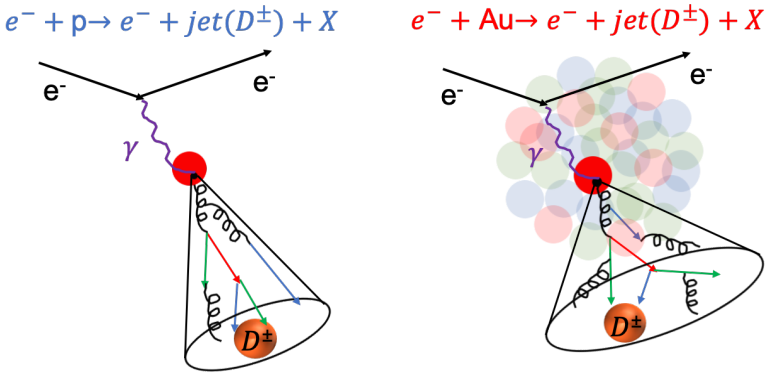
Nuclear transport coefficient



- Heavy quark nuclear transport properties are predicted to be distinctly different from light quarks, giving unique discriminating power between different models.

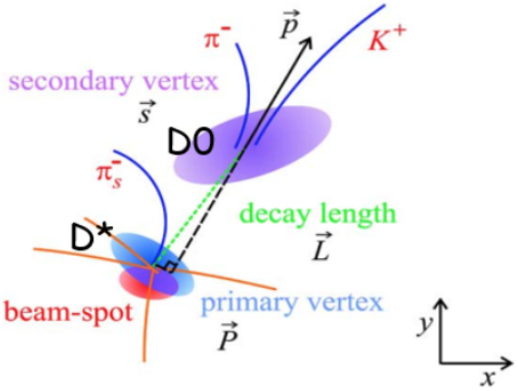
How to measure heavy quarks in experiments?

- At the EIC, hadrons or jets which contain heavy quarks can be identified by detectors using their unique lifetime and masses.



Particle	Mass (GeV/c²)	Average decay length
D±	1.869	312 micron
D⁰	1.864	123 micron
B±	5.279	491 micron
B⁰	5.280	456 micron

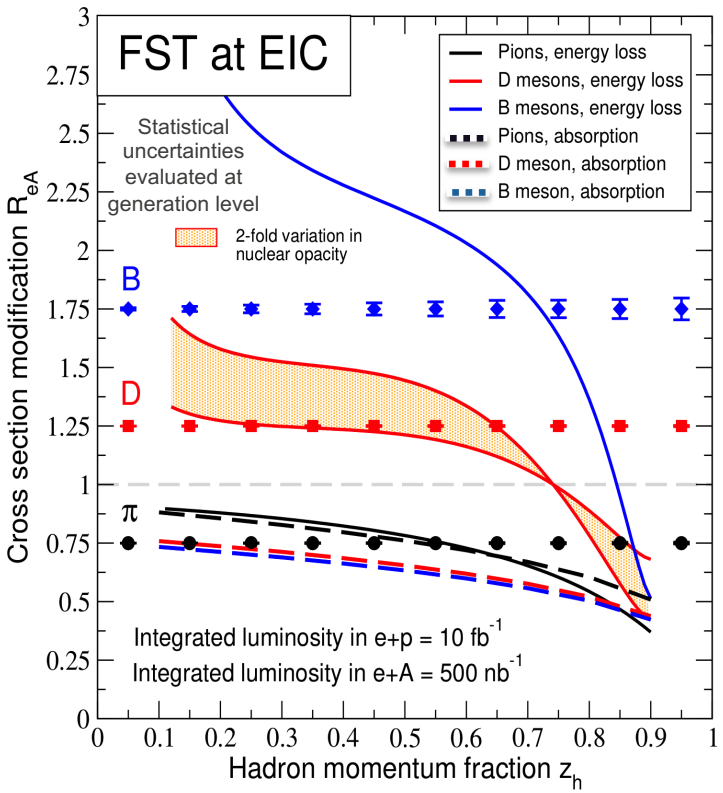
- Physics-driven detector performance requirements:
  - Fine spatial resolution (<100 μm) for displaced vertex reconstruction.
  - Fast timing resolution to suppress backgrounds from neighboring collisions.
  - Low material budgets to maintain fine hit resolution.



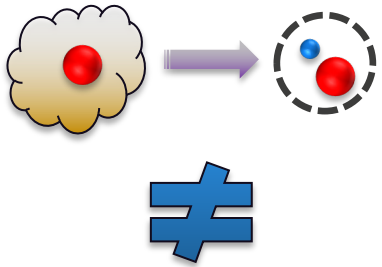
Heavy flavor physics observables at the EIC to probe hadronization in medium

- Calculations done in the energy loss approach:
  - **Tremendous discriminating power** between models of energy loss and hadronization in matter.
  - Can **constrain nuclear opacities & transport properties to 20%.**
- Strong discriminating power provided by heavy flavor measurements to separate different nuclear effects.

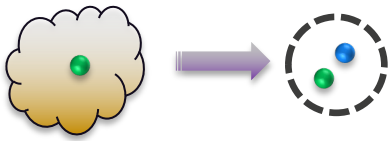
EPJ Web of Conferences 235, 04002 (2020)



Heavy quark fragmentation modification in e+A collisions



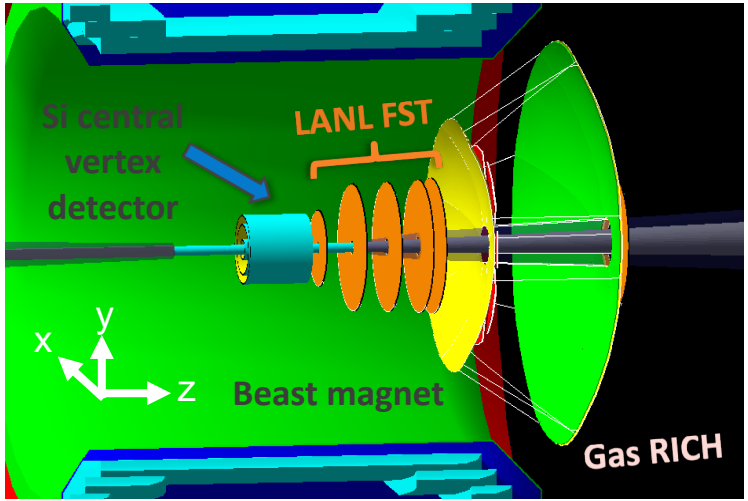
Light quark fragmentation modification in e+A collisions



Conceptual design of the proposed Forward Silicon Tracking detector for the EIC

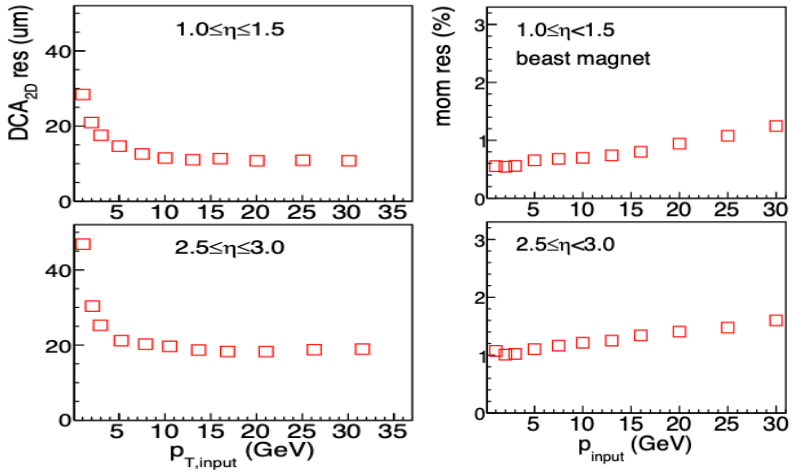
- GEANT4 simulation within the Fun4All framework:
  - Assumed mid-rapidity silicon vertex detector with 5 barrel layers based on the Monolithic Active Pixel Sensor (MAPS) type technology.
  - Forward-rapidity silicon tracking detector (FST) with $1.0 < \eta < 3.5$: 3 planes of MAPS silicon detector and 2 forward planes of HV-MAPS silicon detector.

LANL FST integrated inside the EIC



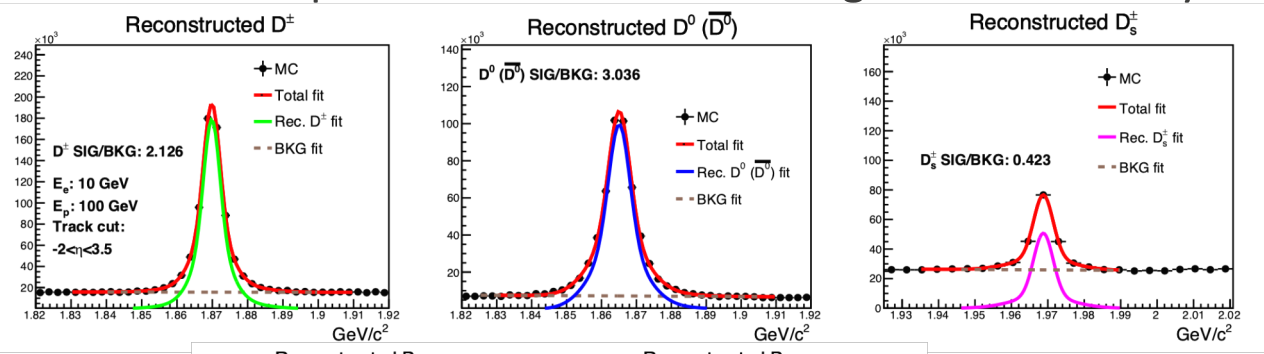
arXiv:2009.02888

LANL FST tracking performance meets the open heavy flavor reconstruction requirements



Reconstructed heavy flavor hadron with the proposed FST in simulation

- The full analysis framework which includes the event generation (PYTHIA), detector response in GEANT4 simulation, beam remnant & QCD background, and hadron reconstruction algorithm have been setup.
- Mass distributions of reconstructed D-meson and B-meson family in 10 GeV electron and 100 GeV proton collisions with integrated luminosity: 10 fb^{-1}.

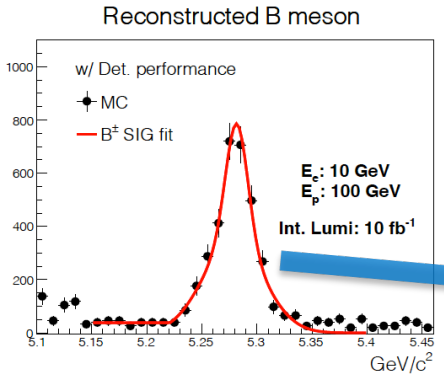


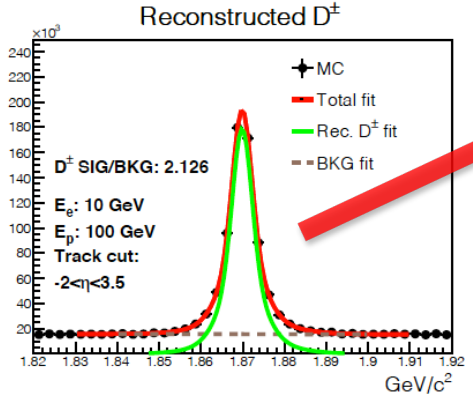
arXiv:2009.02888

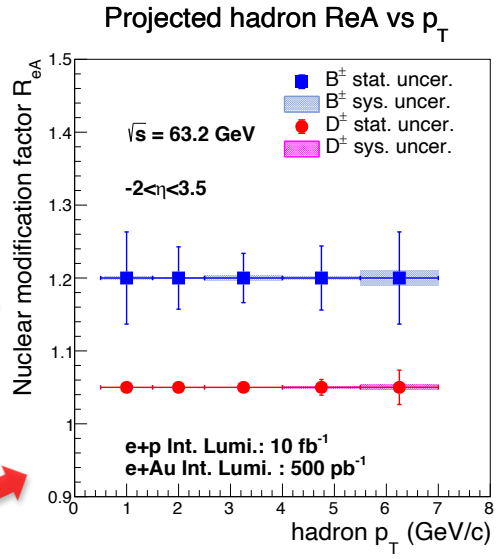
- Central, backward and forward tracking performance.
- Primary vertex resolution: 20-35 (μm) depends on the track multiplicity.
- 95% K/π/p separation over all the acceptance.
- Charged track clusters with a decay length (DCA) cut.

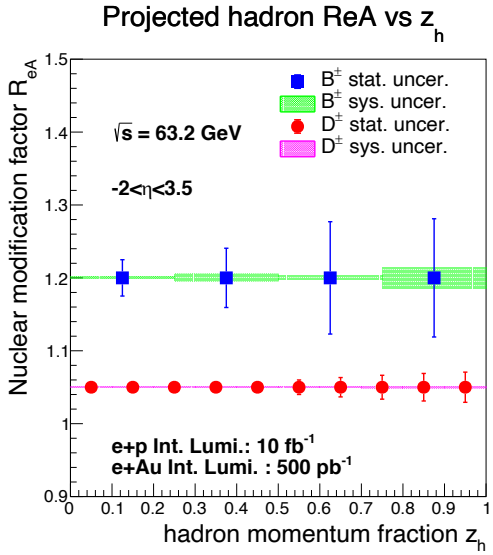
Flavor dependent nuclear modification factor projections for reconstructed hadrons

- Inclusive flavor dependent hadron nuclear modification factor R_{eA} projection in 10+100 GeV e+Au collisions.







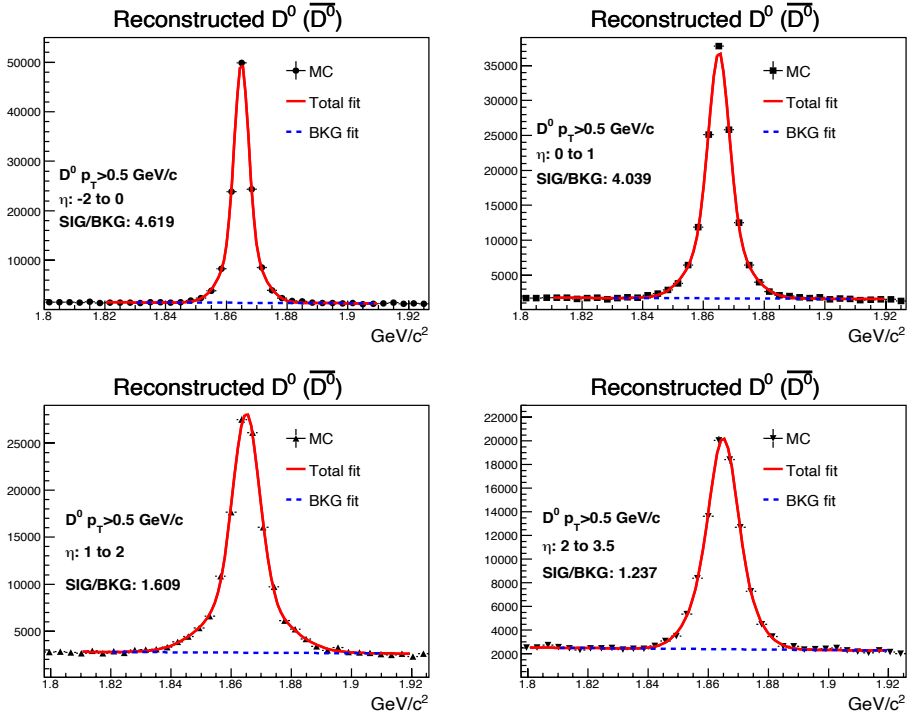


- Good statistical uncertainties can be achieved by reconstructed heavy flavor hadrons.
- Can provide sufficient discriminator power to separate different model predictions.

Separate the kinematics: pseudorapidity dependence

- Heavy flavor produced in different pseudopadity regions experience different initial and final state effects.

η dependent reconstructed D^0 mass distribution

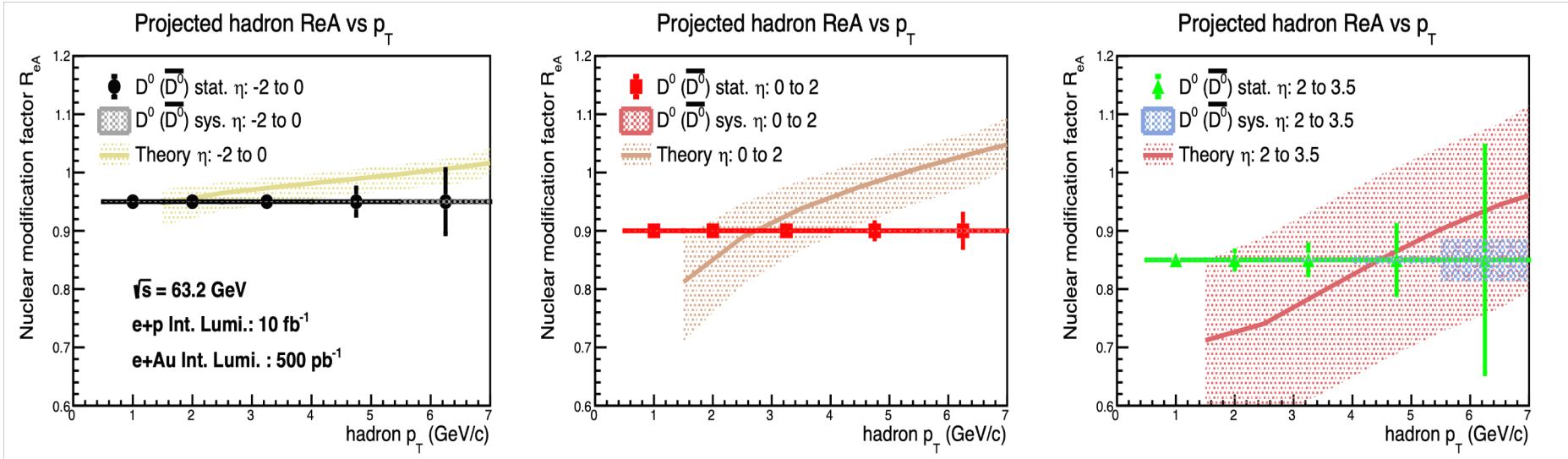


E_e: 10 GeV
E_p: 100 GeV
Int. Lumi: 10 fb^{-1}

arXiv:2009.02888

Separate the kinematics: pseudorapidity dependence

- Heavy flavor measurements especially in the forward regions at the EIC has enhanced sensitivity to the hadronization process in medium and the nuclear transport properties.



p_T dependent R_{eA} for D^0 meson

Theoretical calculations from the HF tomography in EIC, arXiv: 2007.10994

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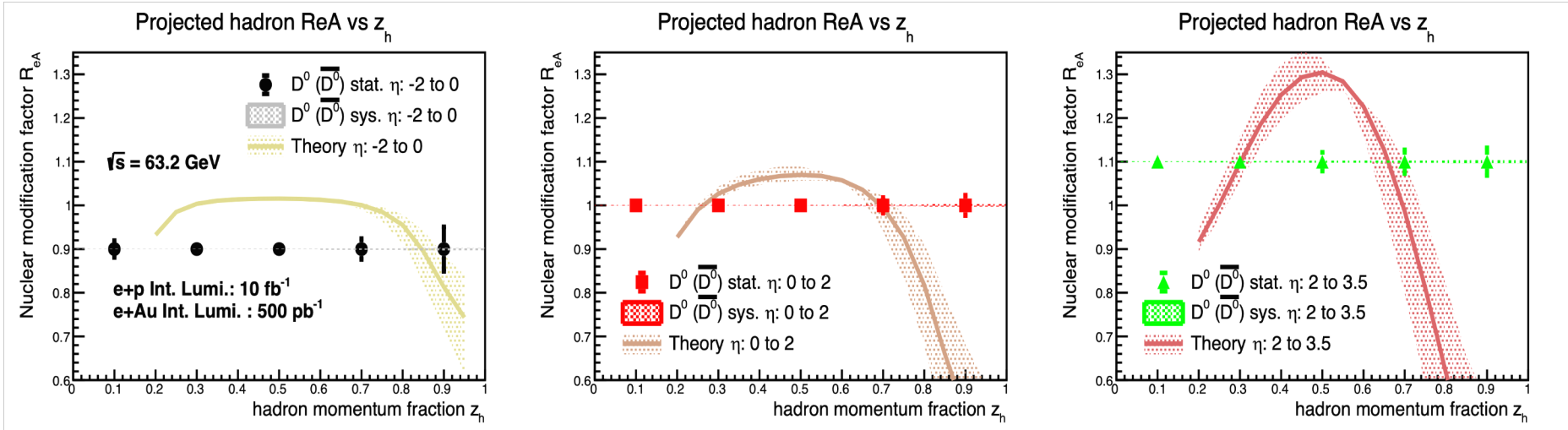

z_h dependent R_{eA} for D^0 meson

Theoretical calculations from the HF tomography in EIC, arXiv: 2007.10994

Separate the kinematics: pseudorapidity dependence

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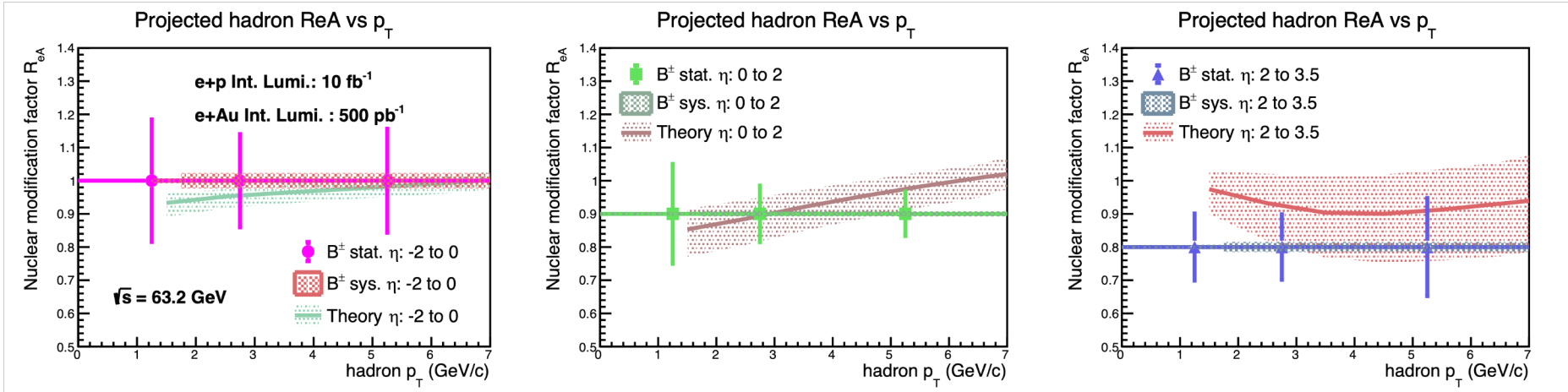


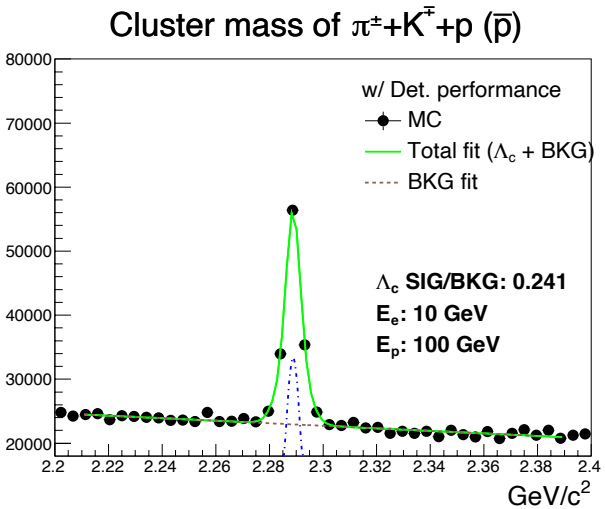
p_T depend R_{eA} for $B^{\pm}$ meson

Theoretical calculations from the HF tomography in EIC, arXiv: 2007.10994

Heavy flavor hadron and jet studies

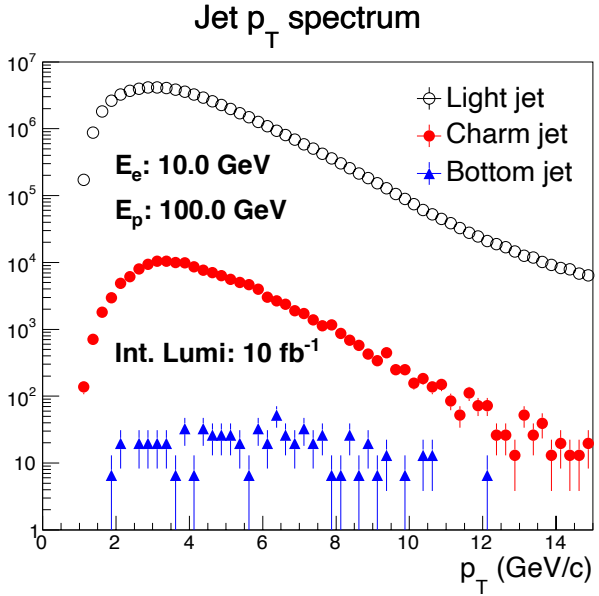
- More reconstructed heavy flavor products have been explored in the full simulation including vertex, tracking and PID performance.

Charm baryon reconstruction



A different approach to the hadronization process such as Λ_c/D ratio to check the impacts from recombination in vacuum/medium.

Flavor tagged jet yields



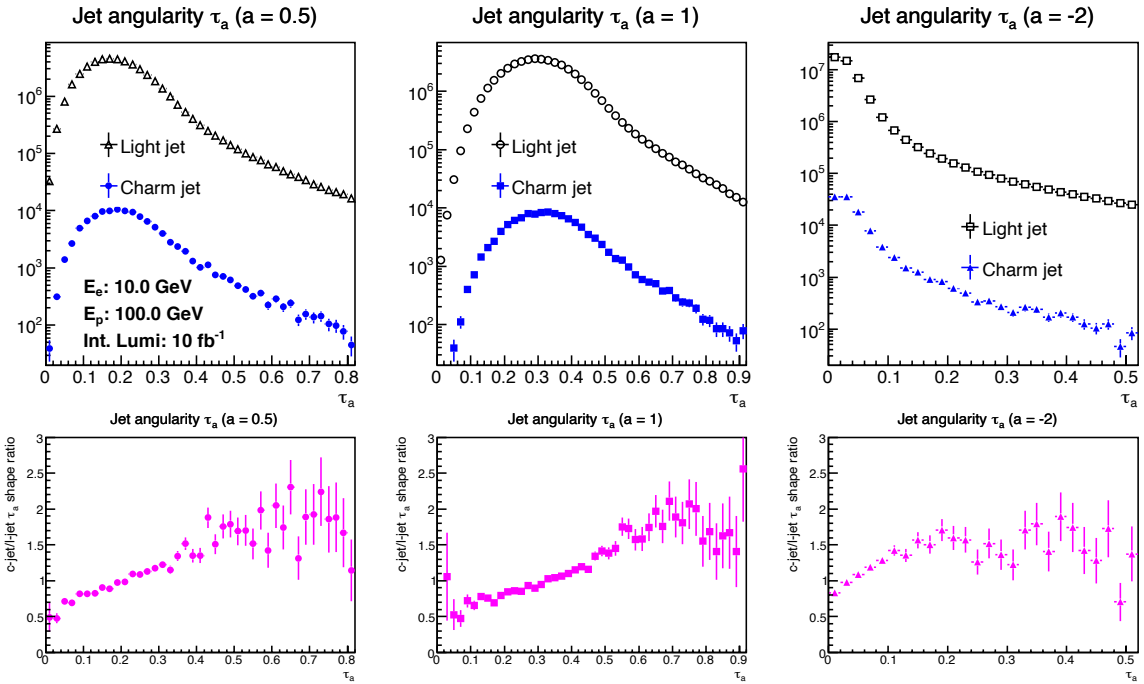
- Jet reconstruction using the anti-k_T algorithm with cone radius 0.8.
- Tag charm-jets with at least one charm hadron inside the jet cone.
- If no heavy flavor hadrons are found inside the jet cone, tag this jet as a light flavor jet.
- Jet yields are not corrected by the reconstruction efficiency yet.

Jet substructure for different flavor jets

- A new probe to explore the hadronization origin and process: jet angularity.

Definition: $$\tau_a \equiv \tau_a^{pp} \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \left(\Delta \mathcal{R}_{iJ}\right)^{2-a}$$ JHEP 1804 (2018) 110

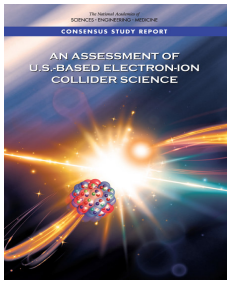
Initial studies in arXiv: 2007.14417

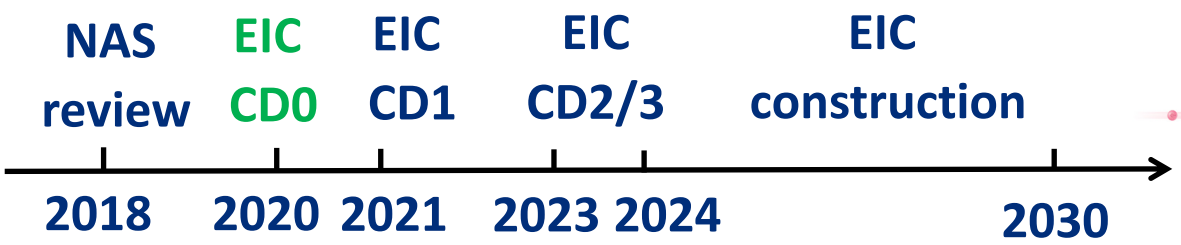


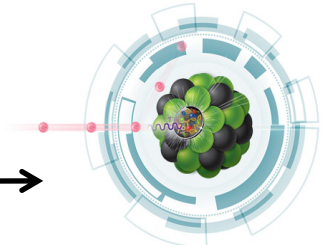
- Jet origin from a quark/gluon can be distinguished from this study.
- Shed light into how quark/gluon recombined into final hadrons with different masses.
- Impacts by nuclear medium effects will be studied in e+A collisions.

Summary and Outlook

- Nice progresses and results have been achieved in the EIC heavy flavor and jet studies with detector performances evaluated in full simulation.
- The new heavy flavor and jet program for the EIC will explore the flavor dependent parton energy loss in medium and the hadronization processes in the poorly constrained kinematic region.
- We look forward to work with more collaborators and contribute to the EIC realization.



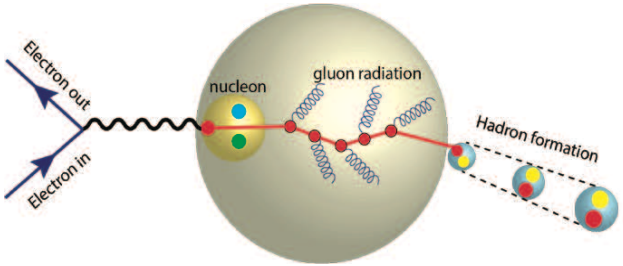




Backup

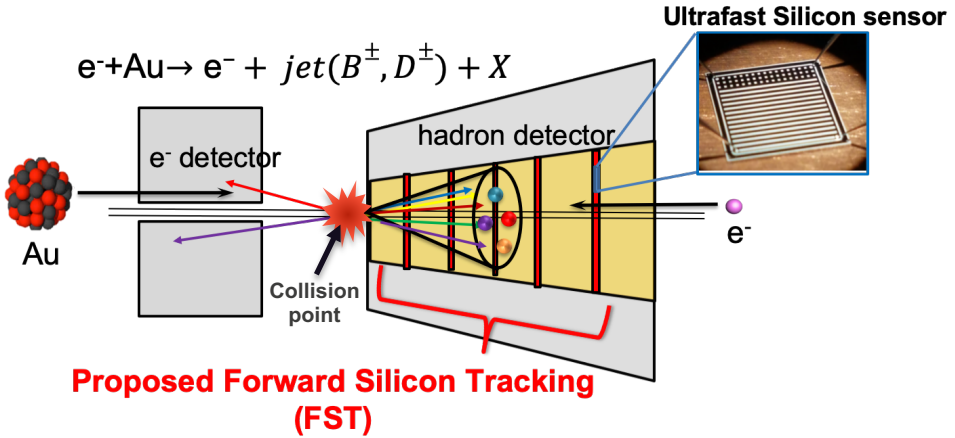
New EIC heavy flavor and jet program at LANL

- An EIC DR (20200022DR), Oct. 2019 to Sep. 2022, is funded by the LANL LDRD office with PI: Ivan Vitev, Co-PI: Xuan Li and 15+ staff/postdocs.



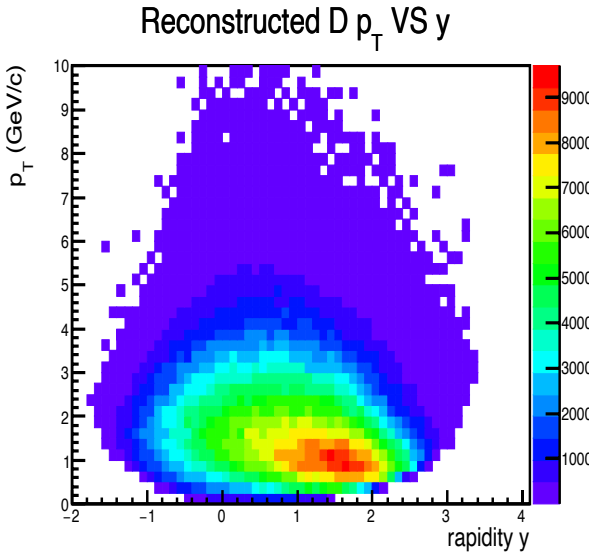
- Through this EIC project at LANL, we will explore hadronization processes and their medium modifications using heavy flavor and jet probes at the EIC.

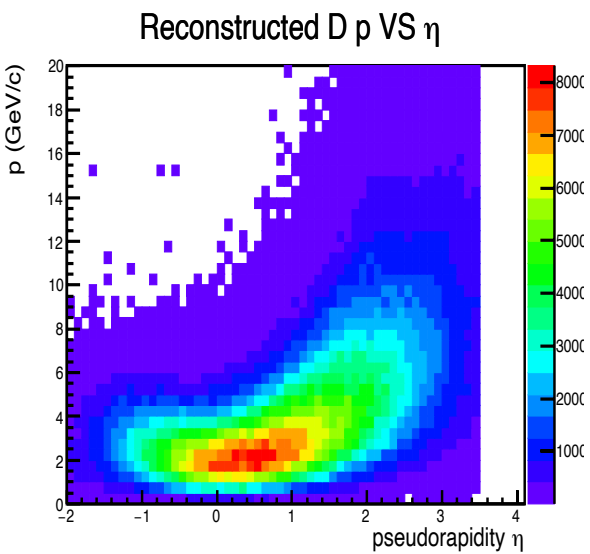
- We will carry out detector R&D for several advanced silicon sensor candidates and complete the conceptual design for a forward silicon tracking detector to realize the EIC heavy flavor and jet physics measurements.

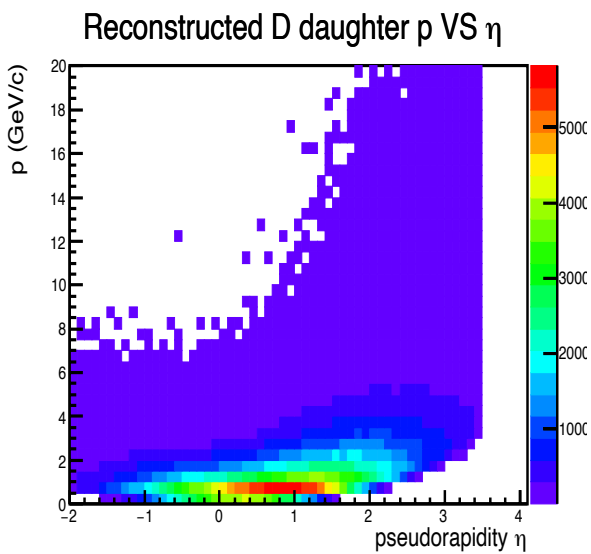


D-meson kinematics

- In 10 GeV electron and 100 GeV proton collisions with integrated luminosity: 10 fb^{-1}

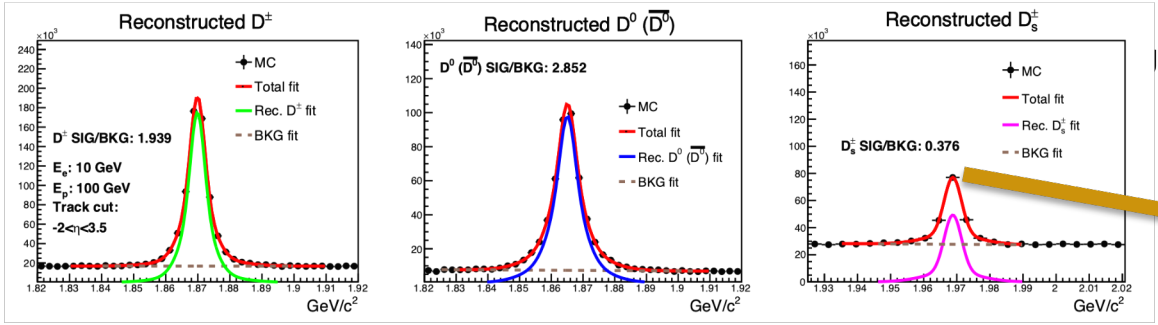


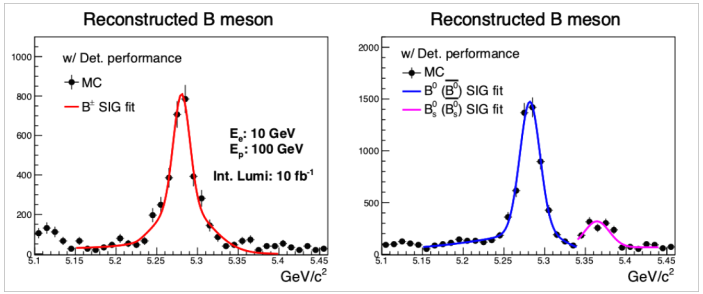


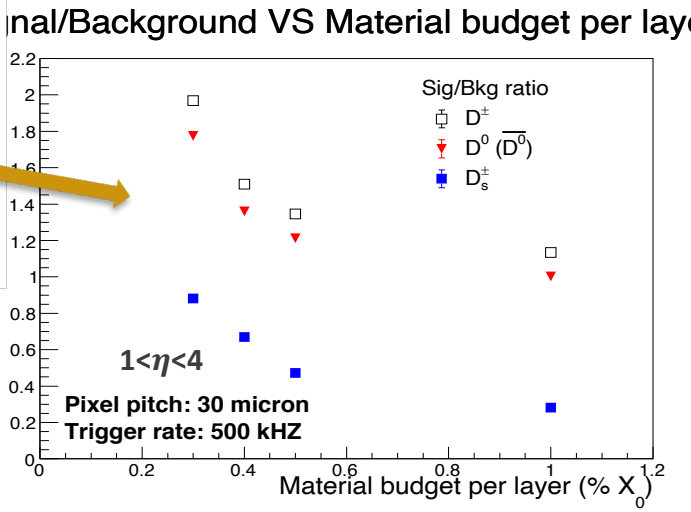


Reconstructed heavy flavor hadron with the proposed FST in simulation

- Heavy flavor physics studies can provide guidance on the EIC detector technology selection and conceptual design.
  - Mass destructions of fully reconstructed D-meson and B-meson.
  - Provide detector requirements based on physics needs.

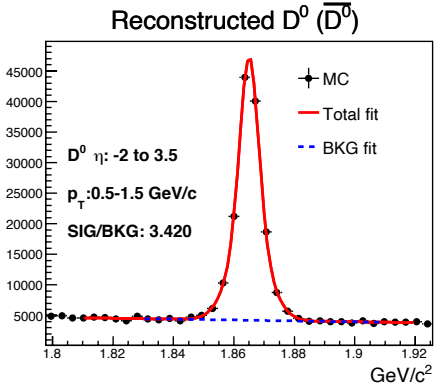


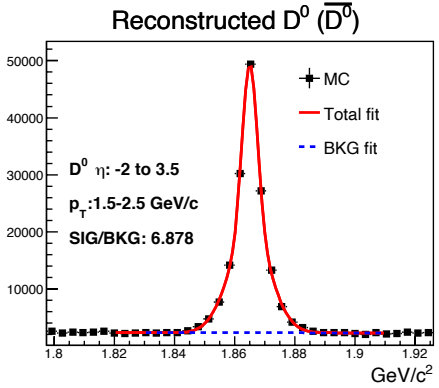


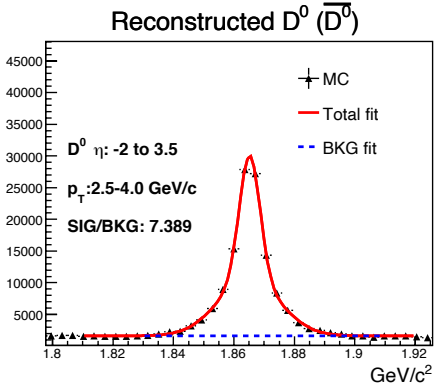


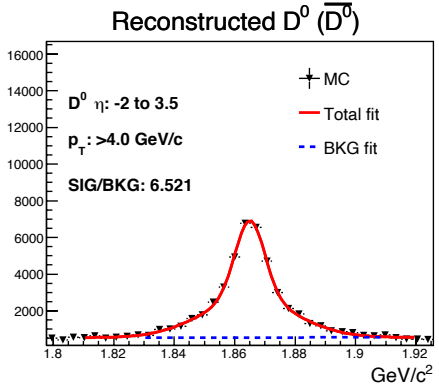
Reconstructed D^0 mass distributions in different p_T bins

- In 10+100 GeV e+p collisions with integrated luminosity at 10 fb^{-1}.





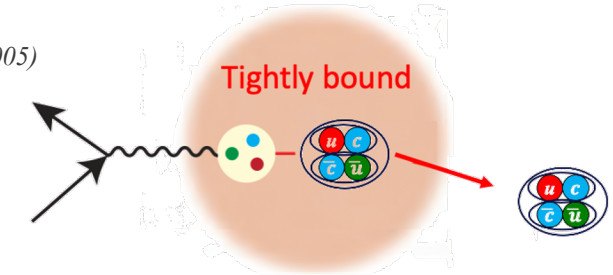




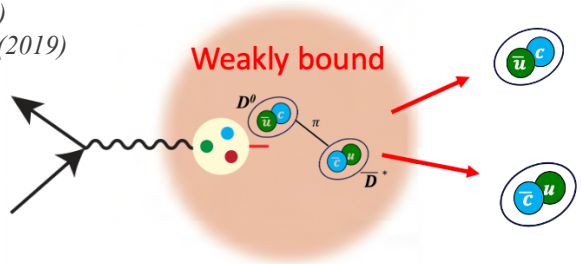
Exotic heavy flavor states at the EIC

- New physics observables are under study.
  - Structure and formation process of new exotic hadrons, e.g. X(3872) can be explored by measuring their suppression in e+A collisions.

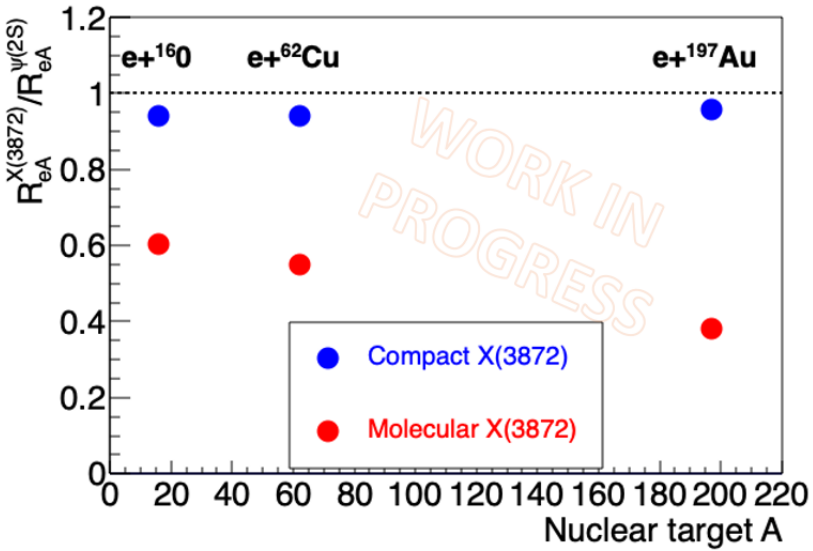
PRD 71, 014028 (2005)
PLB 662 424 (2008)



PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)



Relative modification of X(3872)/ $\psi(2S)$ projection at $\sqrt{s}$ = 63.2GeV



Arleo *et al.*, PRC, 61 054906 (2000)